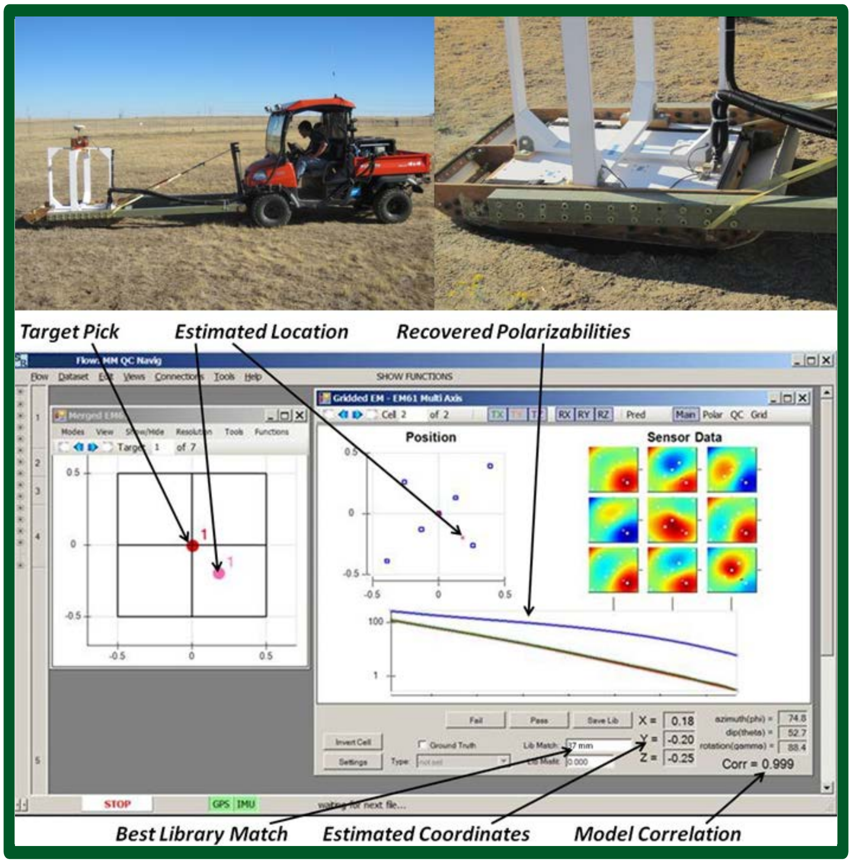
ESTCP
Cost and Performance Report

(MR-201264)



Real Time Quality Control Methods for Cued EMI Data Collection

March 2016

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Jonathan Miller
White River Technologies, Inc.

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
White River Technologies, Inc.
1242 Chestnut Street
Newton, MA 02464

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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14. ABSTRACT
This project evaluated the effectiveness of in-field quality control (QC) procedures during cued electromagnetic induction (EMI) data collection. The primary objective of the demonstration phase of this project was to gain further insight into the field practices that lead to the most effective and efficient cued EMI surveys.

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ACRONYMS AND ABBREVIATIONS

AOI	area of interest
cm	centimeter(s)
DGM	digital geophysical mapping
DQO	data quality objective
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
hr	hour
ISO	Industry Standard Object
IVS	Instrument Verification Strip
mm	millimeter(s)
MMRP	Military Munitions Response Program
MR	Munitions Response
Preac	percentage of reacquisitions
Prec(I)	percentage of recollects resulting in improved classification
QC	quality control
ROC	receiver operating characteristic
SOP	Standard Operating Procedure
TO	task order
TOI	target of interest
USACE	U.S. Army Corps of Engineers
UXO	unexploded ordnance
WMA	Waikoloa Maneuver Area

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This project included contributions throughout the initial development and prove-out stages as well as during the final demonstration of the technology. Thanks to Kevin Kingdon, Dave Lutes, and Barry Zelt (with Sky Research at the time, currently with Black Tusk Geophysics) who provided assistance during the initial development and prove out of the in-field quality control (QC) technology. Thanks also to Elise Goggin (with U.S. Army Corps of Engineers (USACE) Huntsville at the time, currently with Tetra Tech) who provided feedback regarding the utility of the in-field QC software during cued surveys. Mike Sherwin and John Baptiste (Parsons) assisted with the live site technology demonstration by implementing the in-field QC process during their cued MetalMapper survey at the Former Waikoloa Maneuver Area (WMA). Fridon Shubitidze (Dartmouth College and White River Technologies) provided final classification results from the Waikoloa demonstration; these results provided a basis for a retrospective analysis of the in-field QC performance.

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EXECUTIVE SUMMARY

OBJECTIVE OF THE DEMONSTRATION

This project evaluated the effectiveness of in-field quality control (QC) procedures during cued electromagnetic induction (EMI) data collection. The primary objective of the demonstration phase of this project was to gain further insight into the field practices that lead to the most effective and efficient cued EMI surveys. For this demonstration phase, the project team worked with a field team to apply an in-field QC software module during a cued survey of the Former WMA to identify anomalies that may have been insufficiently characterized by the initial data collection. After the survey and final ground truth stages were completed, a retrospective analysis of the WMA data set was performed to identify cases where recollects based on the in-field decision led to an improvement in data quality as well as cases where the recollect was unnecessary (i.e., it did not provide any improvements in classification features).

It should also be noted that during most of the survey, one of the corner receivers for the MetalMapper software was malfunctioning. It is unclear to what extent this faulty receiver influenced the in-field decisions; however, it is possible that it had some effect on the accuracy of in-field target location estimates.

TECHNOLOGY DESCRIPTION

The in-field QC approach includes the use by cued sensor operators of a real-time inversion software module that provides immediate output of features associated with each anomaly investigated by cued EMI data collection. Among the relevant features provided by the software is an estimate of the location of the buried target. If the lateral offset of this estimated location is >30 centimeters (cm) from the center of the cued sensor, the sensor operator can reposition the sensor over the estimated source location and recollect the cued data. Visual interpretation of the sensor location, the estimated target location, and other target features such as electromagnetic polarizabilities is enabled by the in-field QC software.

DEMONSTRATION RESULTS

During the field demonstration of this project, the Parsons field team was supplied with the in-field QC software during their cued MetalMapper survey at the Former Waikoloa Maneuver Area (WMA) on the island of Hawaii. During this survey, the field team encountered 1,032 unique anomaly locations with the MetalMapper. Out of these 1,032 encounters, 231 resulted in recollects based on the estimated target location feedback provided by the in-field QC software.

A retrospective analysis was performed of these MetalMapper data to determine:

- if there were any missed recollect opportunities, i.e., cases where a recollect was not performed, but should have been performed;
- the effectiveness of the in-field QC process by quantifying any improvements in target features obtained by recollecting the data; and
- the efficiency of the in-field QC process by identifying the number of cases where the recollect was unnecessary, i.e., it did not produce better characterization of the target.

These recollect statistics were used to develop estimates of production rates for surveys conducted using the in-field QC approach and for surveys where no in-field recollect decision is made. A summary of the statistics and estimated production rates are as follows:

- out of 1,032 anomalies investigated, of which 231 resulted in a recollect, there was 1 potential missed recollect opportunity;
- out of 231 recollects, 153 recollects appeared to be a result of magnetic geology creating false source locations;
- out of the remaining 78 recollects that were due to legitimate sources (i.e., a metal object), 46 resulted in improvements in target characterization; and
- of the remaining 32 recollects that did not significantly improve target characterization, 11 cases were found where the unnecessary recollect may have been avoided with the application of additional quality metrics (i.e., in addition to the estimated target location metric).

Estimated production rates for surveying with and without the in-field QC process were 23 anomalies/hour (hr) (with in-field QC) and 26 anomalies/hr (without in-field QC).

IMPLEMENTATION ISSUES

The magnetic geology at the site presented the most significant challenge to the technology and contributed to the lower-than-expected production rate for the in-field QC approach. The 46 cases that resulted in quantifiable improvements in target features are an example of the potential benefits of applying in-field QC to cued EMI surveys. Possible ways to improve the efficiency of the technology at challenging sites, such as the WMA, could include improving background selection and removal during in-field QC of the data, or implementing multi-source solvers in the in-field inversion to account for magnetic soil effects and high-target densities.

1.0 INTRODUCTION

This project was undertaken to evaluate and implement quality control (QC) processes for cued electromagnetic induction (EMI) data collection associated with munitions classification surveys. The primary objective of this effort was to establish an optimal set of metrics to inform field teams of the classification quality of the data collected during a cued EMI survey. Incorporating these metrics in a software interface will enable field operators to determine immediately upon acquisition if cued data are of high enough quality to provide useful classification features. This ability to make an informed in-field decision regarding cued EMI data quality has the potential to greatly increase the efficiency of these surveys. Currently, most of the quality analysis for cued EMI surveys is performed off-site by trained analysts. While effective for identifying instances of poor data quality, this method can be costly as it often requires field teams to redeploy to certain areas to reacquire data. Enabling an in-field quality decision will produce immediate corrective actions that will obviate the need for subsequent redeployment and reacquisition by the field team.

1.1 BACKGROUND

The prevalence of innocuous clutter (e.g., scrap, fragmentation) at Munitions Response (MR) sites presents a challenge to remediation efforts that often devote substantial resources to the excavation and identification of these non-hazardous objects. Over the last 5–10 years, the development of advanced EMI sensor arrays that enable multi-axis or multi-angle illumination of cued anomalies has enabled the implementation of methodologies that effectively discriminate clutter from unexploded ordnance (UXO) or other munitions and explosives of concern (MEC). These classification methodologies have the potential to significantly improve the efficiency of production cleanup efforts by reducing the time and costs associated with removal of benign objects; however, collection of high-quality data with advanced sensors is critical to ensuring the effectiveness of these classification algorithms.

Currently, the standard protocol for collecting advanced EMI sensor data includes static data acquisition over anomalies identified (cued) by prior dynamic or digital geophysical mapping (DGM) surveys. These data are typically analyzed by off-site geophysicists upon completion of the cued survey. Often, this analysis results in a number of anomalies that are found to be insufficiently characterized by the initial cued data collection as a result of sub-optimal placement of the EMI sensor during the survey. Subsequently, reacquisition of data is necessary and additional surveying is required. Methods that significantly reduce reacquisitions and improve the overall quality of the data before completion of the initial cued survey will significantly improve the efficiency of production operations.

Providing the field team with the capability to assess data quality immediately following the initial data collection could significantly improve the cued survey process. By removing the off-site analyst from the initial quality decision-making, the field team can take immediate action to reposition and recollect certain targets if deemed necessary. Immediate recollection based on in-field QC can be much more efficient than subsequent reacquisition based on off-site decision-making. Off-site analysis may still be important for identifying complicated target scenarios (e.g., multi-object, magnetic geology); however, many of the reacquires due to common errors such as inaccurate target picking could be replaced by in-field decision-based recollects.

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objective of the demonstration was to gain further insight into the field practices that lead to the most effective and efficient cued EMI surveys. For the demonstration, the project team worked with a field team to apply an in-field QC software module during a cued survey of the Former WMA to identify anomalies that may have been insufficiently characterized by the initial data collection. After the survey and final ground truth stages were completed, a retrospective analysis of the WMA data set was performed to identify cases where recollects based on the in-field decision led to an improvement in data quality as well as cases where the recollect was unnecessary (i.e., the recollect did not provide any improvements in classification features).

By testing the in-field QC process in a live site venue, this demonstration allowed the quantification of the benefits of the approach as well as identification of practical strategies for improving the utility and effectiveness of the approach. The Former WMA site presented a unique set of challenges associated with magnetic soils; however, the suggested improvements to the in-field QC process can be applied generally to sites where background soil response may be variable.

1.3 REGULATORY DRIVERS

Military Munitions Response Program (MMRP) regulations require well-defined Standard Operating Procedures (SOPs) for DGM surveys conducted throughout MR sites. These SOPs include guidelines for conducting daily verification of instrument functionality for both geophysical and positioning equipment used during the survey. Procedures are also defined for the processing and analysis of geophysical data to ensure that the survey produces high-quality data that will indicate the location of any potential contaminants. While the SOPs associated with DGM operations have been refined through years of practice to produce effective survey results, the introduction of cued classification surveys to MMRP projects will require significant modifications to these procedures.

The in-field QC module provides the field team with an intuitive means for assessing not just basic instrument functionality, but also classification quality of the data. Without this immediate feedback, the field team must rely on off-site analysis before knowing if data quality objectives (DQOs) are achieved. Thus, providing the field team with relevant quality metrics is extremely important for ensuring that classification surveys are conducted in an efficient manner and meet the DQOs that are specific to these cued surveys.

2.0 TECHNOLOGY

The basis for the QC module technology is a C++ inversion and classification Application Programming Interface (API) that provides access to physical model (i.e., dipole) inversion algorithms, which can be used to rapidly estimate a variety of model parameters associated with each anomaly. The QC module allows the field team to obtain information about target physical properties immediately after acquiring a cued EMI data file. This information can then be used to assess the quality of the data based on the reliability of these target features.

2.1 TECHNOLOGY DESCRIPTION

The QC module functions as a parallel process to the cued EMI sensor data acquisition software. As such, the QC module does not provide any data acquisition functionality; it is used solely for immediate in-field analysis of the cued sensor data. Existing sensor data acquisition software (e.g., MetalMapper EM3DAcquire) provides the operator with the appropriate interfaces to set the acquisition parameters and trigger an acquisition event; however, all other processes associated with the survey including sensor navigation and data quality analysis are facilitated by the QC module. Following the acquisition of a cued sensor data file, the QC module will immediately load this file and invert the file data. The output of these inversions is subsequently transferred to the operator navigation and QC interfaces that display the various recovered dipole-model parameters (e.g., polarizabilities, location, depth) as well as the raw data channel output. Figure 1**Error! Reference source not found.** shows a screenshot capturing a typical arrangement of these interfaces. It is possible to make both the data acquisition and QC functions available within the same display.

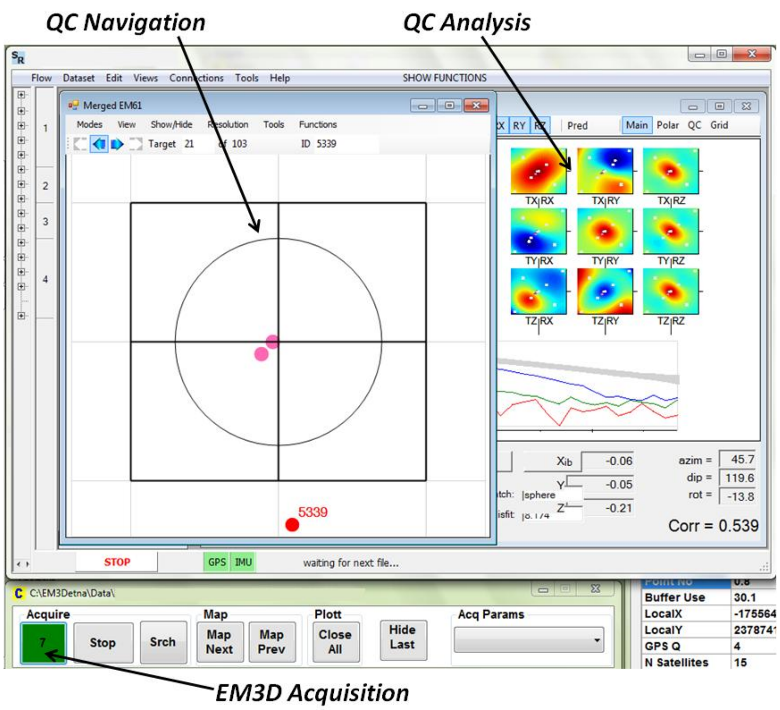

Figure 1. Typical Operator Display Setup Showing QC and Acquisition Interfaces.

The QC module provides the main navigation and analysis interfaces, while EM3D provides the acquisition capability with a simple acquire button.

The QC module navigation interface facilitates sensor positioning and data recollects by displaying target coordinates relative to the cued EMI sensor head location. Target picks identified from analysis of the DGM data can be loaded into the navigation interface to show the location of each anomaly that will be interrogated with the cued EMI sensor. Once the operator selects an anomaly for interrogation, the navigation interface will display both the anomaly location and the sensor head location (Figure 2). As the operator maneuvers the sensor head closer to the anomaly, the navigation display auto-zooms to enable accurate positioning of the sensor over the anomaly. The display provides a sensor frame-of-reference view such that the sensor heading is always directed toward the top of the operator display screen. Once the sensor head is positioned over the anomaly coordinates, the operator acquires a data file. Immediately, the data are inverted and the estimated coordinates of the target are displayed. If necessary, the operator can then reposition the sensor using these new coordinates.

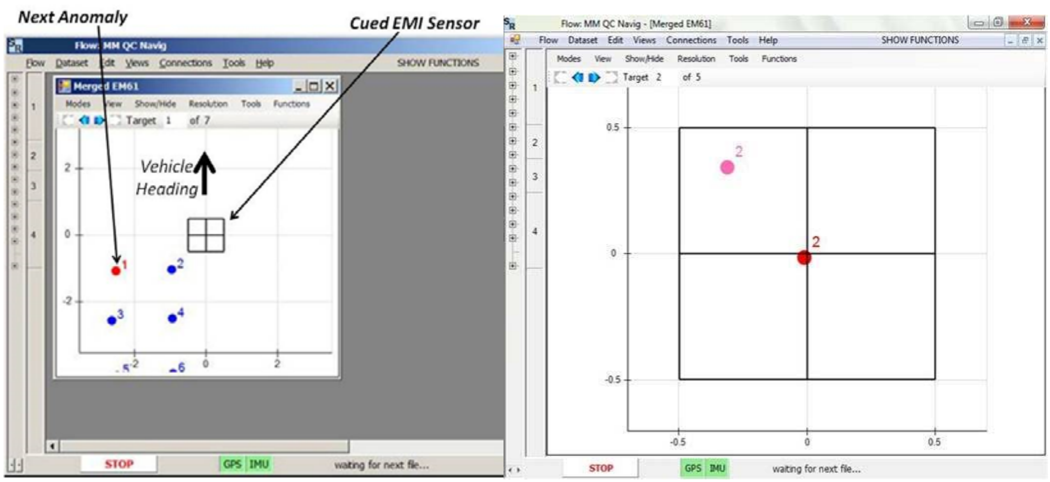

Figure 2. QC Module Navigation Interface.

LEFT: The Navigation Interface Displays the Anomaly Coordinates and the Sensor Location. RIGHT: As the Operator Moves the Sensor Closer to an Anomaly, the Display Performs an Auto-Zoom to Facilitate Accurate Positioning of the Sensor Head Over the Anomaly. After the data are acquired, the QC module updates the navigation display with the estimated target location (pink dot).

In addition to providing the operator with the estimated target location, the QC module also provides information about model parameters that correspond to target features. Classification features, such as target polarizabilities, are compared to those catalogued in a target library. This library corresponds to possible targets of interest (TOIs) that may be located at the site. The TOI library is built from data sets collected in controlled calibration areas within the site (Figure 3). Cued EMI data are collected in a calibration area (i.e., a test pit) over TOIs that are indigenous to the site. Features from these TOIs are then added to the library. During the subsequent cued survey, the QC interface will display the polarizabilities corresponding to each anomaly item and compare them to the library features. The QC interface also indicates the best match TOI. The library can be expanded with additional data sets collected throughout the survey if additional items of interest are found.

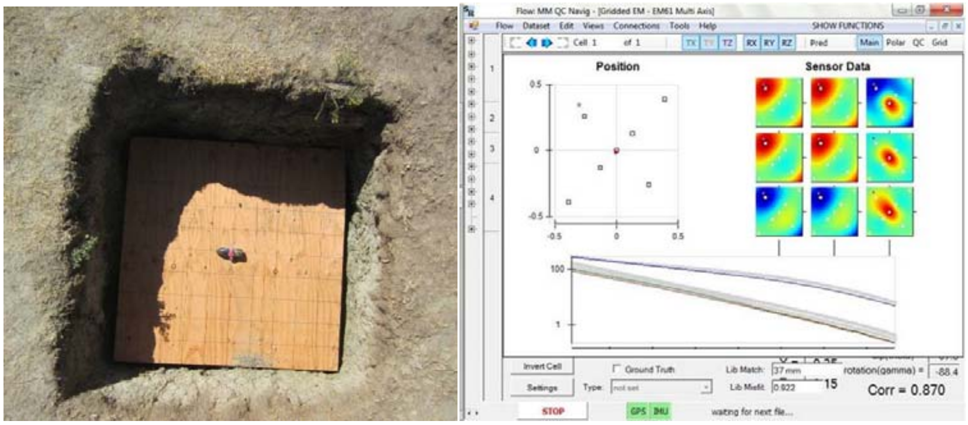

Figure 3. Target Libraries and Features.

LEFT: Target Libraries Are Built from Data Collected in Controlled Calibration Areas within the Site. This Image Shows a 37-mm Projectile Placed in a Test Pit for Library Data Collection. RIGHT: Library Features Are Subsequently Loaded Into the QC Module. The QC interface displays polarizabilities recovered from cued EMI data inversion and compares them to the best-match library features.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The QC module provides several advantages for field teams conducting cued EMI surveys. Currently, there are no commercially available software packages that directly link with advanced sensor output to provide data inversion results in real-time (i.e., immediately after the acquisition of a data file). The capability for sensor operators to obtain inversion parameters, such as estimated target location and target polarizabilities while the sensor is still in proximity to the target pick location, has significant implications for production rates. By providing the operator with the necessary information to assess data quality, the QC module facilitates immediate corrective action based on in-field decisions.

The primary limitation of the technology that became apparent during demonstration of the technology at the Former WMA is the interference of magnetic soils with the real-time inversion output. Retrospective analysis of the Waikoloa data indicated that in many instances, the in-field inversion produced source locations due to geology. Mitigating the effects of magnetic soils poses a significant challenge not just for in-field analysis, but for off-site analysts as well. It may be difficult to remove these effects entirely during the in-field analysis; however, possible solutions could include more frequent background updates to the in-field software, the implementation of a decay fit to indicate to the field operator if the response is likely due to ground conditions, or the implementation of a multi-object inversion that accounts for the ground response in addition to the target response.

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3.0 PERFORMANCE OBJECTIVES

The basis for the field demonstration consisted of a cued (static) MetalMapper survey of anomalies identified from a prior EM-61 DGM survey. The MetalMapper field team conducted a survey of approximately 1,000 anomalies while using the in-field QC module. The team conducted recollects for anomaly locations where the in-field software indicated the presence of a source that was more than 30 centimeters (cm) from the center of the MetalMapper. These procedures led to 231 recollects over the course of the survey. These recollects formed the basis for the retrospective analysis of the QC performance. With the incorporation of the QC module into the survey protocol, there were five possible scenarios that could be used to establish the capabilities and limitations of the technology. These scenarios are as follows:

1. *Cases where no recollect was taken and no recollect was necessary.* These cases accounted for about 80% of the total survey. While these instances did not contribute to any quantitative assessment of the technology performance, they can be used as a baseline to assess the qualitative aspects associated with ease of use and production efficiency.

2. *Cases where no recollect was taken, but was necessary.* Such instances are representative of the technology limitations (i.e., cases where the in-field QC process failed to correctly identify a recollect opportunity). Out of 1,032 anomalies, one case was identified where repositioning and recollecting may have been useful. A possible missed recollect opportunity occurred for seed item WK-1047, where the sole MetalMapper acquisition was collected at an offset of 43 cm from the seed location. Seed WK-1047 was one of the two seeds missed in the classification stage by the project analysts. While it is unclear if repositioning and recollecting would have improved classification features, a 43-cm offset would normally produce a recollect decision. Most likely, this recollect opportunity was missed because of the very strong soil response in this area (post-survey analysis of this anomaly produced ground-like features), which may have produced inaccurate in-field source estimates.

3. *Cases where a recollect was taken, was necessary, and improved the classification features.* This scenario enables a quantitative assessment of the technology performance by providing clear examples of the advantages afforded by the in-field QC process. The analysis indicated that there were 46 cases where the recollect improved classification features associated with the anomaly (in some cases this improvement was significant enough that without the recollect, correct classification may have been difficult).

4. *Cases where the in-field model did not provide accurate characterization of the survey space.* This scenario could include, for example, multi-object cases where the QC module correctly identifies a problematic target, but does not provide the in-field capability to characterize the situation correctly; however, for the WMA survey, the greatest challenge to the in-field QC models was presented by the magnetic geology. Out of the 231 recollects conducted in the WMA survey, 153 of these appeared to be caused by the in-field models indicating a ground source (114 of these occurred in areas where no target was present, 39 occurred in areas where small debris was found).

5. *Cases where a recollect was taken, but was unnecessary.* In other words, this scenario comprises cases where the initial acquisition provided sufficient classification features. During retrospective analysis, 32 cases were found where the initial acquisition produced accurate features for classification and the recollect did not offer any significant improvements. These were cases where the 30-cm recollect rule was likely overly conservative.

Each of the aforementioned scenarios is associated with specific performance objectives. During the post-survey analysis, a set of metrics was applied corresponding to each of these objectives. Table 1 summarizes the performance objectives and corresponding metrics used during retrospective analysis.

Table 1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Identification of all recollect opportunities	Percent of reacquires out of total recollect opportunities	• Off-site QC analysis of all MM initial acquisition files	Preac<0.1
Effective corrective action	Percent recollects out of total recollects resulting in improved target features	• Off-site QC analysis of MM recollects and corresponding initial acq. files	Prec(I)>0.9
Effective in-field characterization	Number of ineffective recollects due to inadequate in-field models	• MM recollect files that did not provide improved features	Insufficient model characterization <5% of total recollect cases
Effective quality metrics	Number of ineffective recollects eliminated	• MM recollect files that did not provide improved features	Any reduction in ineffective recollects
Production rate	Number of unique anomalies surveyed per day (in terms of hourly quotas)	• Field logs, data file time stamps	Site dependent
Qualitative Performance Objectives			
Ease of use		• Operator feedback regarding intuitiveness of display, QC results, and process flows	

MM – MetalMapper, Preac –percentage of reacquisitions, Prec(I) – percentage of recollects resulting in improved classification

4.0 SITE DESCRIPTION

MetalMapper data collected at the Former WMA provide the basis for the technology demonstration. This area comprises approximately 100,000 acres on the northwest portion of the island of Hawaii and includes property that was used as a military training camp and artillery range (Figure 4). Over 100 munitions types including mortars, projectiles, hand grenades, and rockets are known to be present at the site. Details regarding site history and land usage can be found on the U.S. Army Corps of Engineers (USACE) Honolulu District website.[1]

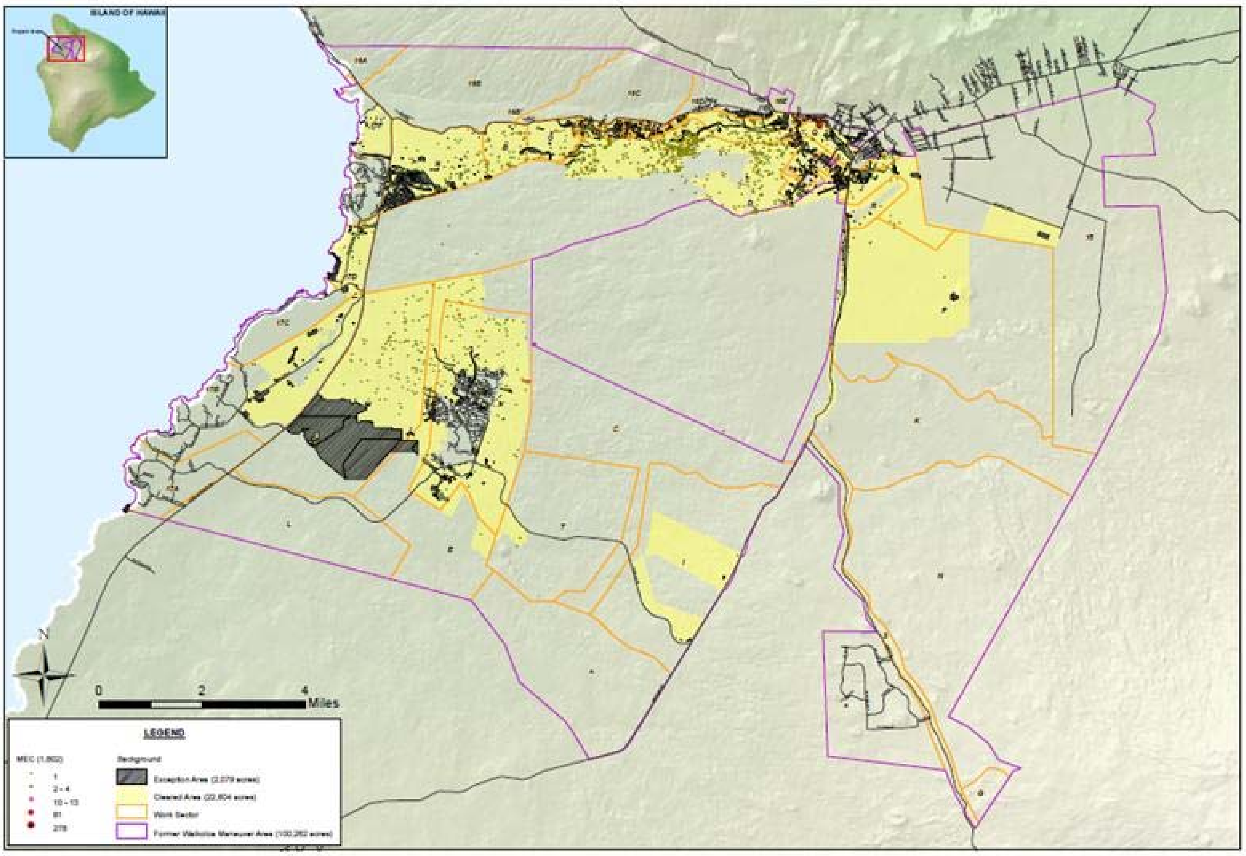

Figure 4. Former WMA (from USACE Waikoloa Map).

The arid site contains sparse vegetation making it suitable for vehicle surveys (Figure 5). The main deployment challenge is the rocky soil, which can damage tires and make transport of equipment across the site difficult. The site is also known to contain significant magnetic geology, which can be problematic for electromagnetic background removal during data processing.

[1] http://www.poh.usace.army.mil/Missions/Environmental/FUDS/Waikoloa.aspx.

Figure 5. Former WMA Site Photos.

MetalMapper data were collected within three areas of interest (AOIs), which included task order (TO)17 and TO20 areas A and B. Each of these areas provided unique magnetic geology that created variable levels of electromagnetic background across the dataset. The magnetic soil influence proved to be one of the most significant challenges in the implementation of classification and in-field QC at this site.

5.0 TEST DESIGN

Demonstration of the in-field QC approach was included as a supplement to ongoing classification studies conducted at the WMA. The unique geology of the WMA offered significant challenges to classification and, therefore, this site was selected for demonstration of several Environmental Security Technology Certification Program (ESTCP) technologies. The project team coordinated with Parsons, who were conducting one of the classification technology demonstrations at this site, to provide the field team a version of the in-field QC module to use during the cued MetalMapper survey of the aforementioned three AOIs. Parsons field personnel were familiar with or had prior experience using the in-field QC software, so transition of the technology was relatively straightforward.

The objective for conducting this demonstration was to obtain data about the utility of the in-field QC process and at the same time to hopefully provide the Parsons team with a technology that would facilitate the technology demonstration. A comprehensive summary of details related to the field activities (e.g., system calibration, data collection, ground truth validation) for this demonstration can be found in the Parsons MR-201104 demonstration report (Van et al., 2015).

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6.0 DATA ANALYSIS AND PRODUCTS

The analysis focused on retrospective interpretation of classification results to determine the effectiveness of the in-field QC process. To obtain relevant data and model parameters from each MetalMapper anomaly, dipole inversions (single and multi-object) were performed for each static MetalMapper file. These inversions provided parameters such as polarizabilities, estimated location, and fit that were subsequently used to obtain metrics for each anomaly. The project team also coordinated with analysts from Dartmouth College (Shubitidze, 2015), who performed primary classification analysis for the WMA site, to identify any specific anomalies that might further elucidate the benefits or shortcomings of the in-field QC method.

6.1 PARAMETER ESTIMATION

To obtain the relevant parameters that would quantify any improvements in recollected data files, dipole inversions were performed for each MetalMapper file. One of the most important steps in this processing stage was the selection of background data that would be used for background removal in each cued data file. Because background response was so variable across the WMA, selection of different backgrounds could produce very different sets of model parameters obtained from each inversion. Background files were initially used that had timestamps closest to those of the associated cued files. If background removal using these files still left a significant background response in the data, other background files collected on the given day would be tried to see if any improvements in background removal could be realized. In some cases, it was only possible to obtain parameters associated with a background response (this was the case, for example, with what turned out to be "no-contact" sources).

After background removal, each static file was inverted using both single and multi-object dipole models. In some cases, the multi-object could be used to constrain the ground response. The polarizabilities, estimated source location, and data/model fit for each inversion were saved for further review of performance metrics.

6.2 PERFORMANCE ANALYSIS

Performance analysis included a review of the aforementioned parameters associated with each recollect anomaly as well as identification of specific anomalies that proved challenging for the final classification stage (i.e., based on retrospective receiver operating characteristic [ROC] curve analysis). The objective metrics were applied to each of these cases.

6.2.1 Objective: Identification of All Recollect Opportunities

Any cued sounding based on a DGM pick could be considered a recollect opportunity; however, one of the biggest issues with identifying these opportunities was whether to include the large number of no-contact encounters (i.e., no target found during excavation) as a potential recollect opportunity. There were a large number of anomalies (about half of all the cued encounters) that could not be attributed to a legitimate source (other than the ground or "hot rocks"). Therefore, these encounters would have a significant impact on the overall recollect statistics. Because these encounters represented an opportunity to make a "no recollect" decision, they were included in the analysis; however, it should be noted that the in-field QC module did not have specific models to reject ground response, therefore, such cases were expected to be challenging for the in-field decision.

6.2.2 Objective: Effective Corrective Action

To determine whether effective corrective action was taken, the recovered model parameters from each recollect were compared to those from the initial acquisition. For recollects associated with TOI, this analysis applied a library fit to the polarizabilities to determine any improvements in target features. For non-TOI encounters, a set of model parameters were applied related to data/model fit, polarizability consistency between successive measurements, and polarizability noise to determine if the recollect provided improvements in features. Finally, for cases where strong ground response was observed, the polarizability decay was assessed to determine whether the features were associated with a metal object or the ground response.

6.2.3 Objective: Effective In-Field Characterization

For each recollect case that did not lead to improved target features, the reason that classification quality was not improved was identified. Because of the interest particularly in cases where the in-field models did not accurately characterize the target space, data/model fits and ground truth records were evaluated to determine if, for example, multiple targets in the area may have led to misguided placement of the sensor. The polarizability decay was also assessed to determine if ground response likely had any significant influence on the in-field decision.

6.2.4 Objective: Effective Quality Metrics

For recollect cases where the initial acquisition provided sufficient characterization of the anomaly, the application of alternative metrics to support a recollect decision was evaluated. Also evaluated was whether the positioning requirements (30 cm or closer) for the initial acquisition were overly stringent and resulted in too many recollects. The goal was to determine if these unnecessary recollects could be avoided without risking any reduction in data quality.

6.2.5 Objective: Production Rate

To establish any efficiency gains resulting from the in-field QC process, the production rates corresponding to the in-field QC protocol and the standard data collection protocol (no in-field QC) were evaluated based on time stamps recorded in the data files. For example, the data time stamps in several groups of consecutively recorded MetalMapper files were used to establish the average, ideal production rates for both data collection methods. Basing this analysis on the time stamp information ensured that production rate estimates were not influenced by inadvertent down time (e.g., for system transport across the site or hardware troubleshooting) that would be atypical of standard MetalMapper surveys.

7.0 PERFORMANCE ASSESSMENT

The following is a summary of the recollect statistics for the WMA MetalMapper survey:

- Out of 1,032 total anomaly encounters, there were 231 unique recollects;
- Out of 104 TOI encounters, there were 18 unique recollects;
- Out of 393 non-TOI (debris) encounters, there were 99 unique recollects; and
- Out of 535 no-contact (no target) encounters, there were 114 unique recollects.

These statistics provide the basis for the analysis of the performance objectives.

7.1 OBJECTIVE: IDENTIFICATION OF ALL RECOLLECT OPPORTUNITIES

To determine if there were any missed recollect opportunities during the WMA survey, cases where the final MetalMapper location was >30 cm from an excavated source were identified. Three potential cases were found, as discussed here.

The first case involved anomaly WK-73—a 37-millimeter (mm) seed buried at 11 cm depth. In this case, the initial (and only) MetalMapper file associated with this anomaly was acquired at an offset of 75 cm. This anomaly was problematic for analysts because the only features obtained were associated with a ground response due to the large offset. While repositioning over the seed location would undoubtedly have provided better data for characterizing the anomaly, it was not thought that this was an instance where the in-field QC failed. A 75-cm offset placed the seed well outside the footprint of the sensor. Under ideal conditions (i.e., no significant soil response or presence of other nearby anomalies), it is possible that the in-field model could have located a source this far from the sensor and provided some guidance for better positioning; however, given the challenges posed by field conditions, accurate features would not typically be expected to be obtained from a source located this far from the sensor. This case represented an error in the initial positioning of the sensor and was therefore removed from the list for classification analysis.

The other two cases involved anomalies WK-1027 and WK-1047, which were a small Industry Standard Object (ISO) seed and a 60-mm seed, respectively. These two seeds proved problematic for the classification analysts as evidenced by the ROC curve shown in Figure 6.

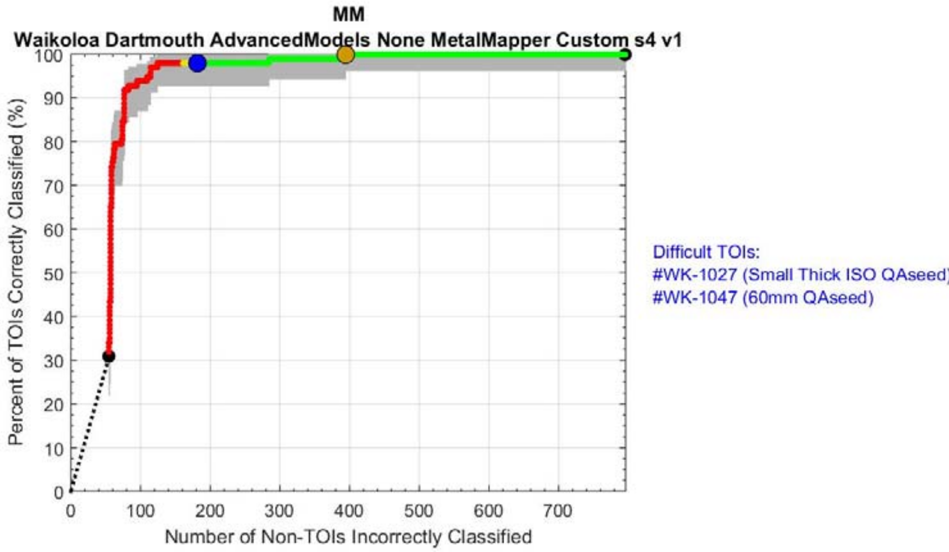

Figure 6. Independent Scoring Results for Dartmouth College WMA MetalMapper Analysis Indicate Two Difficult Targets: WK-1027 and WK-1047.

In both of these cases, the features obtained during analysis appeared to be dominated or degraded by the ground response. Thus, insufficient background removal appeared to be the major cause of the classification failure; however, the project team wanted to determine if the sensor positioning could have been a factor as well. Since neither of these cases included a recollect, whether the initial sensor location may have contributed to the incorrect classification decision was assessed.

For seed WK-1027, the sensor was located 27 cm from the target. Since this offset is within the conservative 30-cm objective radius, this case was not considered to be a failure of the in-field QC model. It is possible that given the small size of the object and the dominant ground response, positioning the center of the sensor closer to the object could have provided better results in this case; however, it is believed that this case is more representative of the challenges posed by magnetic soils than of the limitations of the in-field QC approach.

For seed WK-1047, the sensor was located 43 cm from the target. This offset is significantly outside the 30-cm objective radius and, therefore, this is considered to be a missed recollect opportunity. While it is likely that under ideal conditions (i.e., no significant soil response or presence of other nearby anomalies) it would be possible to obtain accurate classification features at a 43-cm offset, the presence of a significant ground response makes it very difficult to obtain representative features with the sensor at this location. Most likely, if the in-field QC model had access to a representative background at this location, a better QC decision could have been made at the time.

To obtain the metric for this objective, the number of remaining recollect opportunities (1,032 – 231 = 801) were identified. Out of 801 possible additional recollect opportunities, it is believed that there is only one case where repositioning the sensor may have led to a better classification result. Therefore, the percentage of reacquisitions (Preac) <0.1 was achieved.

7.2 OBJECTIVE: EFFECTIVE CORRECTIVE ACTION

To determine whether the recollects provided significant improvements in the classification quality of the data, the features obtained from each recollect were analyzed and compared to those of the associated initial acquisition. For recollects over TOI, improvements were quantified by assessing the polarizability fit to the relevant TOI library. Figure 7 shows an example of an effective recollect over a 37-mm seed.

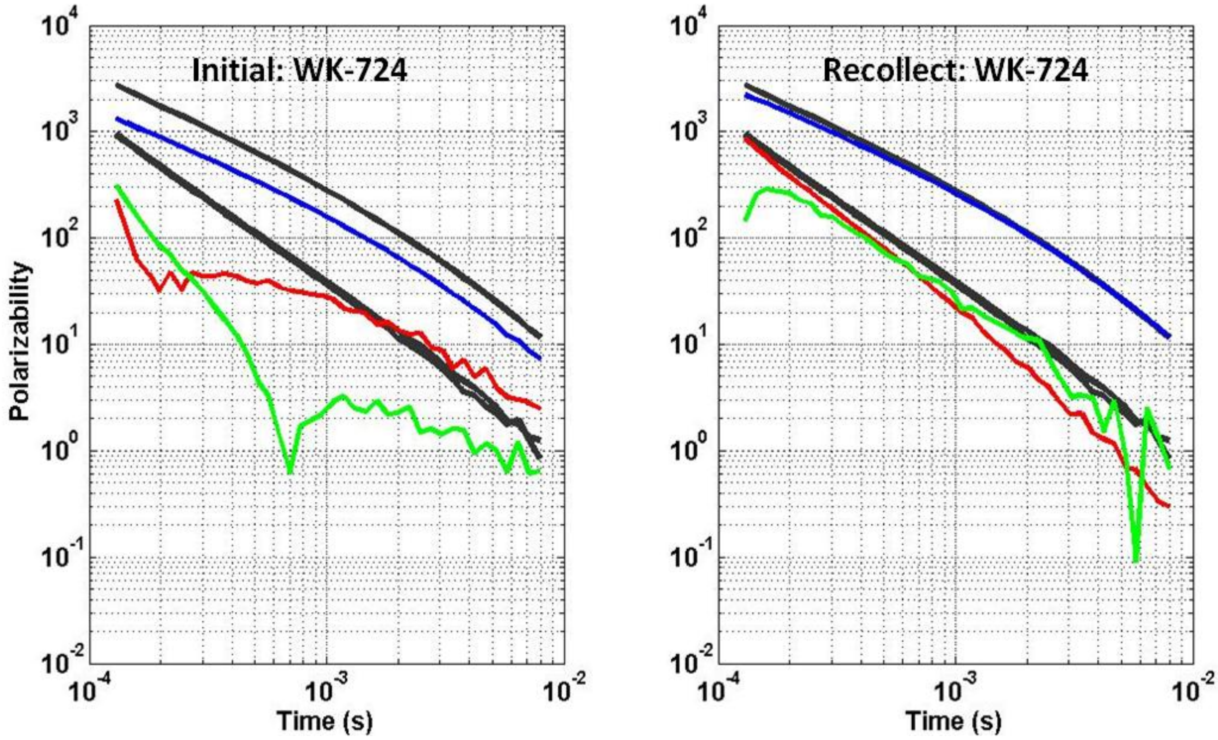

Figure 7. Polarizabilities Obtained from Two Different Acquisitions Over WK-724, a 37-mm Seed.

For the initial acquisition, the sensor was offset 34 cm from the target. The recollect placed the sensor at an offset of 13 cm from the target. The polarizabilities (blue, red, and green lines) show a much better match to the library (dark grey lines) in the recollect.

The results shown in Figure 7 reflect a good example of improvements achieved by recollecting with better sensor positioning (13 cm lateral offset in the recollect compared to 34 cm lateral offset in the initial acquisition). The initial acquisition did not enable accurate recovery of the polarizabilities; however, the recollect provided features that matched closely to the library. Review of the data showed that the initial acquisition may have been influenced by a small, nearby piece of clutter that was less evident in the recollect location.

For recollects over non-TOI (i.e., frag or other debris), any significant improvements using model parameters derived from the inversion of the data were quantified. For example, Figure 8 compares the polarizabilities obtained from initial and recollect acquisitions over munition debris (WK-1053, fuze clip).

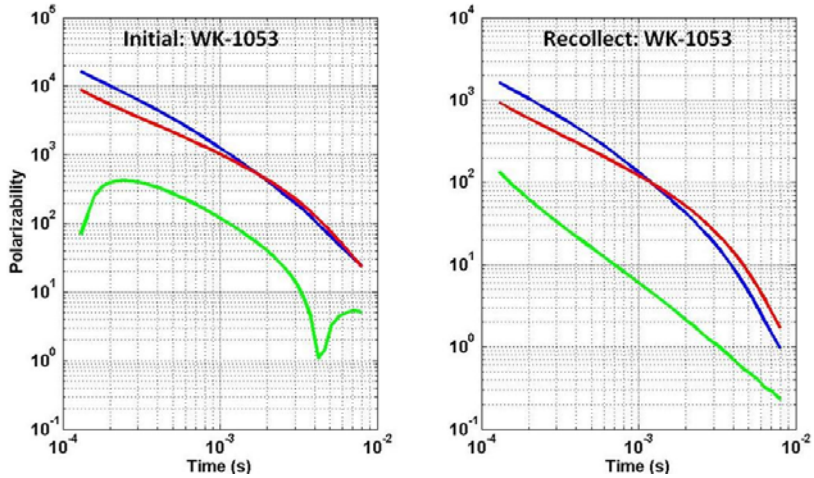

Figure 8. Polarizabilities Obtained from Two Different Acquisitions Over WK-1053, a Piece of Munition Debris.

The recollect provides better constraint on the third polarizability (green line).

The results shown in Figure 8 were quantified using model noise and model consistency metrics. Further validation was later provided by library matching to polarizabilities obtained from other fuze clips encountered throughout the site. The recollect shown in Figure 8 provided features that were much more consistent with those from other encounters with this target, which turned out to be a common debris item at the site.

Over the course of this analysis, several encounters were discovered where the recollect provided an entirely different set of features from those of the initial acquisition. These cases occurred when the initial acquisition was dominated by the ground response and the recollect was able to resolve the features associated with the actual target. A visual QC check of the polarizabilities could identify these cases as shown in Figure 9.

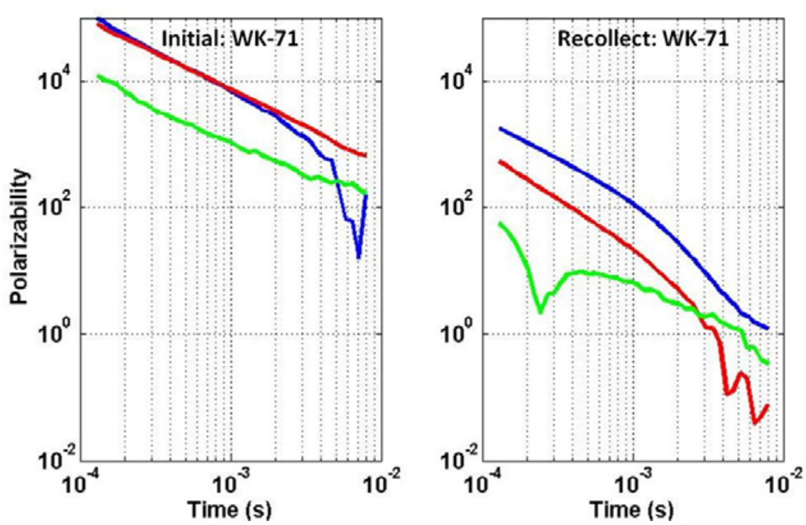

Figure 9. Example of the Recollect Providing Better Resolution of Target Features.

In this case, the initial acquisition produced polarizabilities dominated by the ground response. The recollect provides features that more accurately represent the actual target (a piece of frag).

Overall, 46 cases were found where the recollect provided significant improvements in target features. While this number is a minority of the 231 total recollects, it should be noted that most of the recollects (153 cases) appeared to be due to inaccurate source locations created by the ground response. Counting these ground recollects, a percentage of recollects resulting in improved classification (Prec(I)) = 0.19 is obtained (i.e., 46 out of 231 recollects resulted in improved features). Disregarding the ground recollects, a Prec(I) = 0.59 is obtained (i.e., 46 out of 78 recollects provided improvements). Both of these values fall short of the objective Prec(I) = 0.9 (i.e., 90% of recollects result in improved target features).

7.3 OBJECTIVE: EFFECTIVE IN-FIELD CHARACTERIZATION

The majority of cases where the recollect did not lead to improved target features appeared to be a result of insufficient background removal or inadequate ground models. An example of this is provided in Figure 10, which shows the initial acquisition and the recollect over anomaly WK-68, a piece of frag.

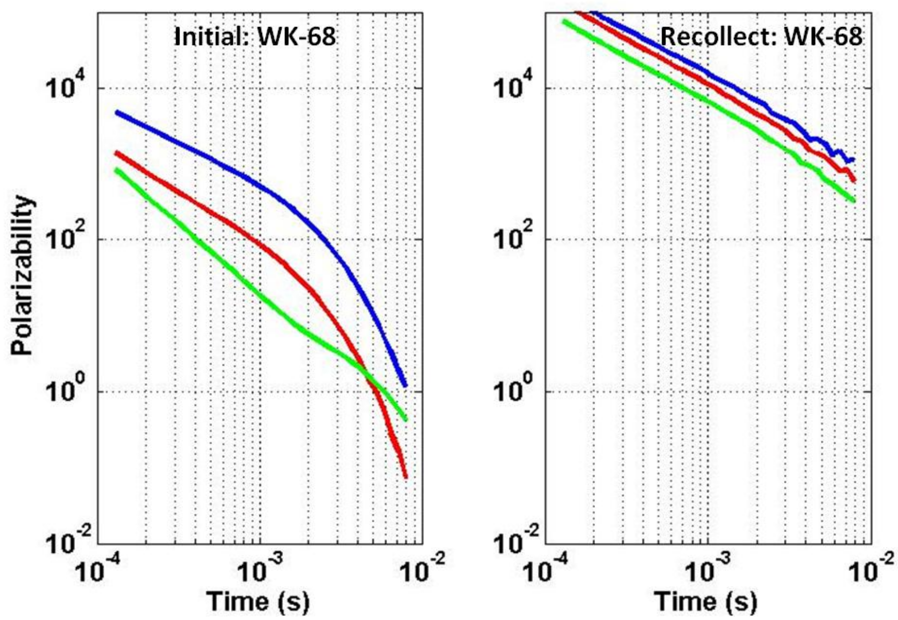

Figure 10. Polarizabilities Associated with Anomaly WK-68, a Piece of Frag.

Here the initial acquisition shows good resolution of target features; however, the recollect provides features dominated by the ground response.

Multiple objects did not appear to present any significant problems for the in-field QC. No cases were found where an absence of multi-source solvers in the in-field models led to a poor classification of a target. While there were several instances where multiple sources were found within the search area, most of these cases included a number of small debris items. For TOI as small as 20 mm, it is possible these cases could have been problematic; however, the smallest TOI encountered during the survey was 37 mm, which was not small enough to be masked by any of the nearby debris items.

Out of the 231 recollects, 153 cases were found where the soil response appeared to influence the in-field QC decision resulting in insufficient characterization of the area. This number is significantly greater than the objective 5% of total recollects; however, given the known challenges associated with the site's geology, and the absence of any methods to mitigate these effects in the in-field software, these results are reasonable.

7.4 OBJECTIVE: EFFECTIVE QUALITY METRICS

The remainder of ineffective recollects (i.e., recollects that did not improve characterization and that were not a result of magnetic geology or multiple target influence) provided an opportunity to test quality metrics other than estimated location to see if these unnecessary recollects could have been avoided by using additional metrics. Overall, 32 cases were found where the initial acquisition provided sufficient characterization and the recollect did not offer any significant improvements. Figure 11 and Figure 12 show two examples (anomalies WK-267 and WK-169) of such cases.

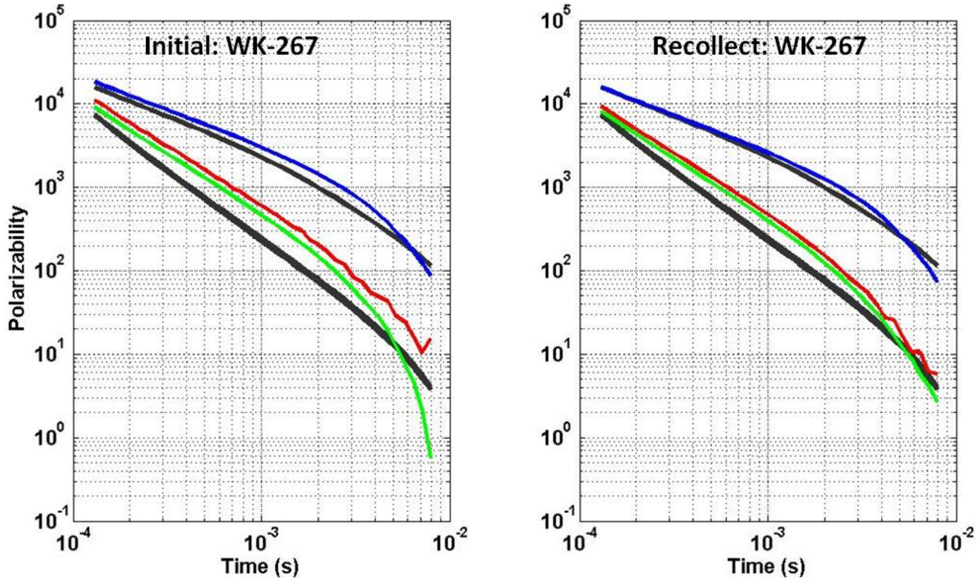

Figure 11. Polarizabilities Recovered from the Initial Acquisition Data (Left) and the Recollect Data (Right).

These polarizabilities correspond to anomaly WK-267, a medium ISO seed. Here the recollect was unnecessary.

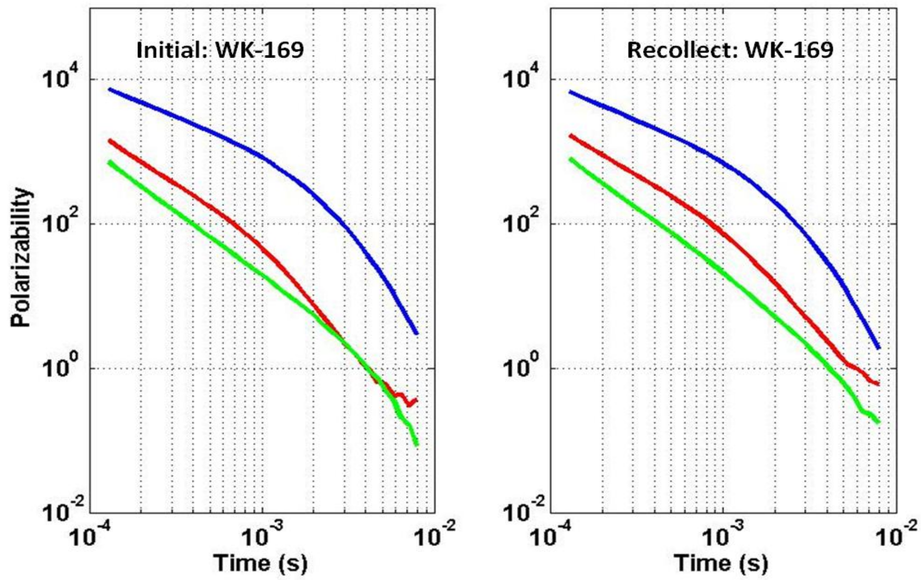

Figure 12. Polarizabilities Recovered from the Initial Acquisition Data (Left) and the Recollect Data (Right).

These polarizabilities correspond to anomaly WK-169, a piece of frag. Here the recollect was unnecessary.

For several of these cases, the initial acquisition was very close to the 30-cm offset threshold used to make a recollect decision (e.g., 32 cm for WK-267, and 26 cm for WK-169). For cases like these where the anomaly is close to the offset threshold, including a data/model fit metric into the decision could boost operator confidence. This information is currently provided to the operator and it could be factored into the decision. For example, in both the WK-267 and WK-169 initial encounters, the data/model fit was very high (>98%). If the initial acquisition is within, for example, 25–40 cm of the anomaly, perhaps a fit ≥98% could lead to a no-recollect decision.

While the fit could be a good supportive metric in these cases, it is not always reliable. Consider, for example, anomaly WK-880, a fuze clip (Figure 13). Both the initial encounter (37-cm offset) and the recollect (9-cm offset) provided very good fits (>98% each); however, it is clear that the third polarizability (green line in Figure 13) is not well constrained in the initial encounter data (although it could be argued that these initial encounter features are sufficient for making a classification decision). In this case, a model noise metric (i.e., polarizability noise) could be added to the decision flow to determine whether a recollect is necessary. In this case, the initial set of polarizabilities does not pass the model noise metric, leading to a recollect decision.

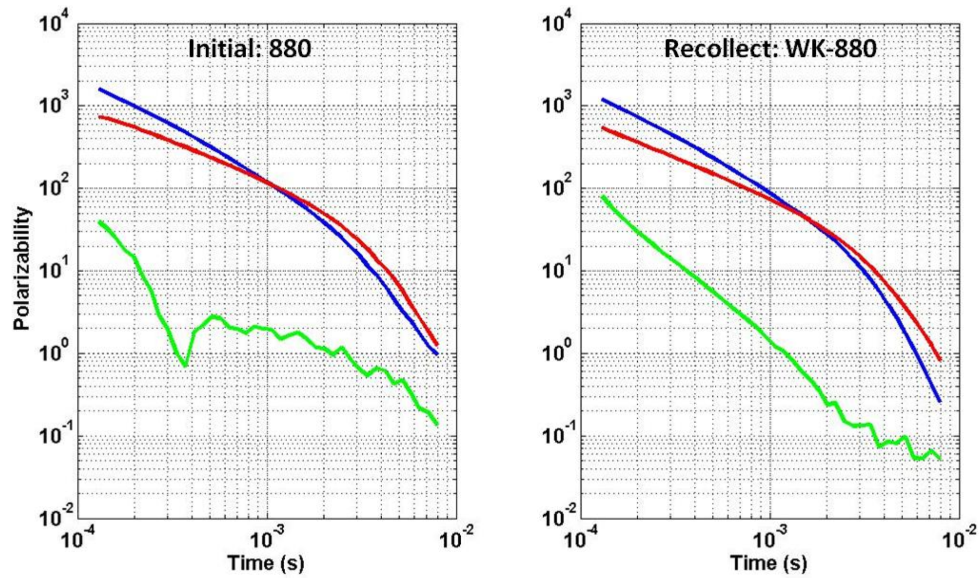

Figure 13. Polarizabilities Recovered from the Initial Acquisition Data (Left) and the Recollect Data (Right).

These polarizabilities correspond to anomaly WK-880, a fuze clip. The initial data do not fully constrain the third polarizability (green line) and indicate that the recollect was beneficial.

Model fit provides a good indication that the target is well represented by the model parameters. For example, cases where there are interfering sources, such as ground response or other nearby targets, will produce a reduced fit value. Obtaining a high model fit (i.e., >98%), however, does not necessarily indicate that the model parameters are well constrained. The model noise metric is a measure of the polarizability stability and is an indication of whether or not the data provide good constraint on the model parameters. For example, the initial features shown in Figure 8 and Figure 13 indicate that the third polarizability (green line) is unstable and is, therefore, not well constrained. Taken together, these two metrics could be a robust way to assess whether the initial acquisition data provide accurate classification features.

One possible solution for reducing unnecessary recollects is to include these additional metrics into the decision flow. This information is currently available to the operator; however, it could be possible to make this flow automated to provide a recollect/no recollect decision for the operator. Figure 14 presents a possible flow for including additional metrics. While reducing unnecessary recollects is not critical to improving the outcome of the in-field QC process, it could improve the efficiency of the process.

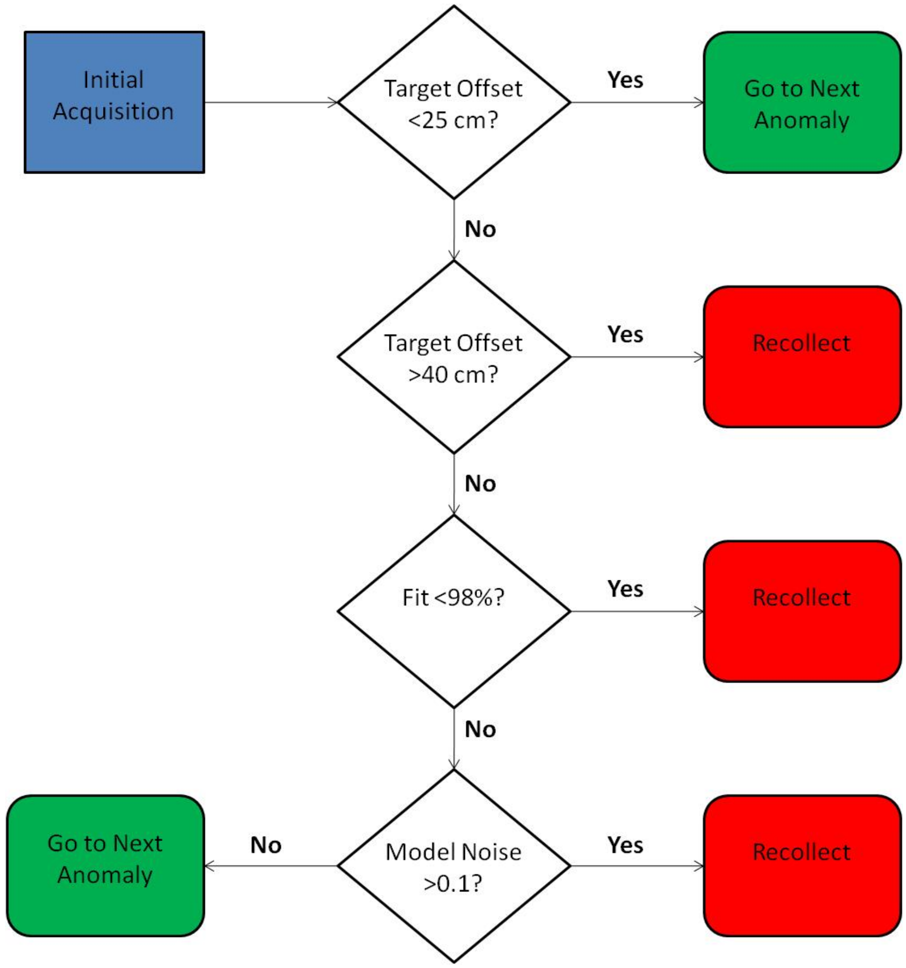

Figure 14. Possible Decision Flow for In-Field QC.

This decision flow incorporates the additional fit and model noise metrics along with the primary target location metric to support the decision to recollect or not. The objective of this type of decision flow would be to reduce unnecessary recollects that may occur within some margin of error of the 30-cm offset threshold (e.g., 25–40 cm). All metrics including the offset threshold could be adjusted for site-specific requirements, such as smallest TOI or target density, to reflect different tolerances for data recollects.

Out of the 32 cases where the recollect did not improve target features, 11 cases were found that could have potentially been avoided by incorporating the basic fit and model noise metrics into the decision flow. In the retrospective analysis, the fit metric threshold was set to a conservative value (≥98%) such that these additional metrics could be implemented without creating missed recollect opportunities. Setting a high value for the fit metric was an effective way to avoid missed recollect opportunities as most of the "necessary" recollect cases analyzed failed the initial fit metric ≥98%.

7.5 OBJECTIVE: PRODUCTION RATE

For the production rate analysis, the project team wanted to establish representative production rates for surveys performed with and without the in-field QC. Factors specific to the WMA survey, such as equipment down-time and equipment transport time, were not wanted to influence these rates.

Therefore, the project team relied on the time stamp information from groups of consecutively recorded data files that were created during periods of uninterrupted survey time. The time stamp analysis indicated that with the in-field QC process, the field team could achieve an ideal baseline production rate of 23 unique anomalies/hr. Without the in-field QC process in place, the field team could achieve an ideal baseline production rate of 27 unique anomalies/hr.

When these production rates were adjusted based on the number of necessary recollects for the survey, the true production rate for the in-field QC approach remained at 23 anomalies/hr while the standard approach true production rate dropped to 26 anomalies/hr.

Using this analysis, it appears that performing a survey without in-field decision-based recollects may have been slightly more efficient than applying the in-field QC approach; however, a number of additional factors should be considered. First, a large number of recollects (about 66%) appeared to be a result of ground response (i.e., no contacts) for which there is currently no in-field mitigation process. This large number of unnecessary recollects lowered the average baseline production rate for the in-field QC survey. Second, the number of necessary recollects (those that led to improved target features) was relatively small at 46. This number did not significantly lower the adjusted rate for the standard approach (it dropped from 27/hr to 26/hr). Therefore, it might be expected that sites without difficult geology or sites that contain higher anomaly densities could potentially alter these production rates significantly.

Another way to assess the impact of the in-field QC method on production rate is to view it specifically in the context of the WMA survey. The actual production rates achieved during the survey were lower than the 23/hr rate would indicate. This lower rate was due primarily to the difficult terrain, which slowed transport of the sensor across larger areas of the site (Van et al., 2015). Actual production rates achieved were in the range of 65–75 anomalies/day. Based on the data time stamp information, it is estimated that the average time required to perform a recollect was about 105 seconds. Viewed in this context, the 231 recollects probably added about 6–7 hrs of additional survey time. Going back and reacquiring 46 anomalies (the necessary recollects) would have probably taken 1–2 days of additional survey time given that these anomalies were spread across different AOIs within the site. Thus, it is likely that even with the recollects associated with ground response, the in-field QC enabled a slightly more efficient survey for this particular site.

7.6 QUALITATIVE OBJECTIVES

Ease-of-use has been discussed with a number of MetalMapper system operators who have performed surveys with the in-field QC software. Overall, feedback has been positive. One of the most common reports is that having an inversion-based location that can be used to position the sensor provides the operator with additional confidence in the quality of the data. Another positive response has been utility of the software for performing Instrument Verification Strip (IVS) activities. Having the in-field output for the polarizabilities and estimated location of each IVS item provides immediate and quantitative feedback about the functionality of the system hardware.

8.0 COST ASSESSMENT

The MetalMapper survey costs can be found in the MR-201104 final report (Van et al., 2015). Total costs applying the in-field QC approach during the survey were $76,100 for cued acquisition of 1,032 unique anomalies. This figure produces an average rate of $74/anomaly. This rate can be adjusted for the standard method (i.e., no in-field recollects) using the aforementioned true production rates for both methods. An additional cost component is the time required for set up and installation of the in-field QC software.

8.1 COST DRIVERS

Production rate analysis indicates that the cost per anomaly might have been lower if the survey had been applied without recollects, due to the fact that a large number of recollects (153) were associated with ground response, which produced inaccurate source locations. Additionally, there were relatively few recollects (46 out of 231 total) that provided significant improvements in target features. These cost drivers reflect the challenges that were specific to the WMA site.

The true cost comparison of the two methods for the WMA site may be somewhat different than what is reflected by the cost per anomaly in Table 2 if the specific conditions of the site are considered. For example, it is unlikely that reacquisition of 46 targets could actually be accomplished in ~2 hrs. In reality, this would likely have required 1–2 additional survey days given that these anomalies covered three different AOIs and transport between these areas was time-consuming. It is expected that the true costs for each method at this particular site were comparable, if not slightly lower, for the in-field QC method.

Table 2. Cost Model for In-Field QC for Cued EMI Surveys.

Approach	Data to be Tracked
Survey costs (in-field QC)	$74/anomaly • Assumes 1,032 unique anomalies surveyed at a rate of 23 unique anomalies/hr • Includes 153 recollects associated with ground response
Survey costs (standard)	$65/anomaly • Assumes 1,032 unique anomalies surveyed at a rate of 26 unique anomalies/hr • Includes 46 reacquisitions
Training/installation	$2,400 • Approximately ½ day of survey time

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9.0 IMPLEMENTATION ISSUES

The greatest challenge to effective implementation of the in-field QC process at the WMA site was the presence of significant magnetic geology throughout the AOIs. The retrospective analysis of the survey data indicated that a significant portion of recollects based on the in-field decision were a result of the soil response (153 out of 231). After analyzing the recollect data, the following recommendations were developed that could improve the effectiveness and efficiency of the in-field QC process at other challenging sites:

- One approach to enable in-field mitigation of magnetic geology could be to enhance the background selection and removal process of the in-field software. For example, multiple background locations based on DGM analysis of magnetic geology in the survey area could be included in the background selection process for the in-field software. Background files collected at these locations could be loaded into the module and automatically selected based on location of the sensor. Proximity to different background locations in the site would drive the selection of the optimal background file to apply before inverting each subsequent data file.

- In many cases, however, there will not be an ideal background file. This was evident in the post-survey processing when it became apparent that none of the background files collected on a given day were adequate for removing the ground response for a number of anomaly encounters. In cases such as these, more sophisticated inversion strategies are required. For example, replicating the ground response by constraining the location of a deep dipole source during inversion has been effective for isolating the response from targets buried in magnetic soil (e.g., Pasion et al., 2012). It could be an effective approach to include a two-source solver in the in-field model that would allow one source to be constrained to represent the ground response. Decay fit metrics could be applied to determine if the constrained source does indeed produce ground-like features that indicate the presence of significant magnetic geology.

- While the WMA survey did not appear to produce many cases where multiple objects influenced the in-field QC decision, there are sites where this could be an issue. In some cases, implementing a multi-source solver could be effective for isolating the ground response (see above) as well as for isolating responses from multiple, closely-spaced targets.

- Finally, using quality metrics in addition to the estimated source location could prove useful for eliminating unnecessary recollects. In cases where the target is isolated from any interfering sources (e.g., ground response, other nearby targets, low signal-to-noise ratio), the 30-cm offset threshold may be overly stringent. While eliminating unnecessary recollects may not be critical to improving the effectiveness of the process, it could improve the efficiency of the process, leading to better overall cost performance. Incorporating other metrics into the decision flow (Figure 14, for example) could eliminate recollects in some of these cases where the initial acquisition provides adequate characterization of the target.

While the WMA survey elucidated several challenges for the in-field QC process, it is believed that overall the process proved beneficial for the survey. There were 46 cases where the recollect provided significant improvements in the characterization of the target and most likely improved the final classification result. Given the challenges of transporting and moving equipment around the different AOIs, these 46 anomalies would likely have added an additional 1–2 days of surveying if they had not been recollected based on the in-field decision (for comparison, it is estimated that the 231 total recollects for the survey added 6–7 hrs of actual survey time over the course of field activities). Additionally, there are other benefits to providing the field team with immediate inversion-based metrics including the immediate feedback about instrument functionality during IVS activities.

It should also be noted that during most of the survey, one of the corner receivers on the MetalMapper was malfunctioning. It is unclear to what extent this faulty receiver influenced the in-field decisions; however, it is possible that it had some effect on the accuracy of in-field target location estimates.

It is likely that a large number of sites could benefit from implementing an in-field QC process for cued surveys. Applying some of the aforementioned improvements could make the process more effective for particularly challenging sites, such as those containing magnetic geology or high anomaly densities.

10.0 REFERENCES

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APPENDIX A POINTS OF CONTACT

Point of Contact	Organization	Contact Information	Role in Project
Jonathan Miller	White River Technologies 115 Etna Rd. Lebanon, NH 03766	(603) 678-8387 miller@whiterivertech.com	Principal Investigator
Erik Russell		(603) 678-8387 russell@whiterivertech.com	Project Manager

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ESTCP Office
4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6565 (Phone)
E-mail: estcp@estcp.org
www.serdp-estcp.org